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A REVIEW OF RESEARCH ON DELETERIOUS SUBSTANCES IN CONCRETE AGGREGATES

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by

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Joint Highway Research Project

PURDUE UNIVERSITY
LAFAYETTE INDIANA

TECHNICAL PAPER

A REVIEW OF RESEARCH ON DELETERIOUS SUBSTANCES IN CONCRETE AGGREGATES

TO: K. B. Woods, Director
Joint Highway Research Project

December 18, 1957

FROM: H. L. Michael, Assistant Director

File: 5-9-5
Project C-26-42E

Attached is a report entitled, "A Review of Research on Deleterious Substances in Concrete Aggregates," by R. L. Schuster, Research Assistant on our staff.

This report summarizes the research conducted in the Project Laboratories and in other locations on deleterious substances in concrete aggregates. It was made at the request of the Board at its meeting on September 18, 1957. This action was taken as a result of the Highway Department's new specifications concerning the amount of chert.

The report is presented as information.

Respectfully submitted,

Harold L. Michael

Harold L. Michael, Assistant Director
Joint Highway Research Project

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TECHNICAL PAPER

A REVIEW OF RESEARCH ON DELETERIOUS SUBSTANCES IN CONCRETE AGGREGATES

by

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Joint Highway Research Project
Project No. C-26-42E
File No. 5-9-5

Purdue University
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December 18, 1957

EARLY RESEARCH ON DELETERIOUS SUBSTANCES IN CONCRETE AGGREGATES

The presence of certain rocks, minerals, and other substances may greatly impair the quality of concrete made with aggregates containing only small percentages of these materials. The term "deleterious substances" or "deleterious constituents" has become a common one for describing this class of materials.

Deleterious substances are those which adversely affect the concrete in which they are used. These substances may be categorized on the basis of the nature of their harmful effects (1)[1]. The most harmful class of deleterious materials consists of those which tend to expand disruptively due to induced strains resulting from weathering of the deleterious materials. The most common examples of this class are porous cherts[2], well-indurated clays, and limestones containing expansive clays. Such materials, when frozen in a saturated condition or, in some cases, when merely exposed to water, increase in volume with development of sufficient pressure to cause deep-seated disintegration of the concrete.

In another class of deleterious substances the aggregate particles do not undergo volume changes which tend to disrupt the

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[1] Numbers in parentheses refer to the list of cited references which appears at the end of this report.

[2] Chert may be defined as a dense cryptocrystalline sedimentary rock, composed of chalcedony (microcrystalline fibrous silica and microfibrous amorphous silica or opal) and cryptocrystalline quartz (2). It has a tough splintery to conchoidal fracture. It is commonly white, gray, or blue-gray, but may be brown, black, green, blue, pink, red, or yellow. Flint is a term widely used both as a synonym for chert and as a variety of chert. Tarr (3) states that flint is identical with chert, and recommends that the term be dropped from geologic usage. Although the term flint antedates the term chert, present-day usage favors the latter as the proper designation of the materials to which both terms have been applied (2).

surrounding mortar. Instead they break into numerous smaller pieces due to the inherent structural weaknesses of the particles themselves. Examples of such deleterious substances are clay lumps, ochers, poorly indurated shales, and soft sandstones. Depending on the quantity of these materials used in the concrete, deterioration may be general or more often, may be evidenced primarily by surface pitting or scaling

Other materials which are commonly classified as deleterious are organic impurities and lightweight pieces, including coal, lignite, and wood. Organic impurities generally retard the setting of cement and reduce concrete strength, particularly at early ages. Finely divided coal, lignite, or wood in sufficient quantity will also retard hardening. However, these materials generally occur as small quantities of larger pieces which have no significant effect on the strength of the concrete but may detract from its appearance by producing surface pits.

It has long been recognized that certain types of aggregates have harmful effects on the concrete in which they are used. It was not until the 1920's, however, that much research was begun in this country which attempted to quantify the effects of those materials which were suspected of being deleterious; and, thus, to determine the quantities of these materials that could be included in concrete aggregates. During the construction season of 1923, Reagel (4) noticed a peculiar surface effect on the concrete pavements constructed in certain localities in Missouri. Investigation showed that portions of the surface averaging 1 to 1-1/2 inches in diameter were cracking

loose from the pavement and could be pried out or were later displaced by traffic, leaving a hole with sloping sides from 1/2 inch to 1 inch in depth. On removal of a large number of these "popouts," it was discovered that the piece of pavement loosened always contained a large fragment of chert aggregate at the bottom while the remainder of the piece of aggregate was left forming the bottom of the hole in the pavement. It was evident that the force acting to raise the "pop-out" occurred in all cases through the aggregate. The action never occurred in connection with pieces of limestone, of which the greater part of the coarse aggregate in the pavement consisted, but always just above or through a piece of chert.

Reagel then conducted an investigation which showed that these "popouts" were due to frost action on the pieces of chert. He subjected aggregates which were high in chert content to simple freezing and thawing tests in the laboratory. These tests were conducted on both the loose aggregate and on concrete beams in which the aggregate containing chert was incorporated. They consisted of five cycles of alternate freezing and thawing. The results of these tests showed that the loose chert was seriously affected by the tests and often disintegrated completely. The test beams showed a definite loss of strength; and, in cases where large percentages of chert were included in the aggregate, they often disintegrated to the point where they could not support their own weight.

Reagel noted that the five cycles of freezing and thawing which he used in these tests were considerably fewer than could ordinarily be expected in an average winter season in Missouri. Since five

cycles of freezing and thawing often produced severe disintegration of concrete made from the chert aggregate, he concluded that chert should be limited to the smallest percentage possible in aggregates to be used in the production of concrete.

In 1924, Withey (5) outlined the various tests which had been developed by that time for testing the durability of concrete aggregates. Four types of tests were then in use: (a) the freezing and thawing test, (b) the sodium sulphate soundness test, (c) the sodium chloride test, and (d) the alkali test. Each of these methods was intended to give an accelerated test of the potential durability of the aggregate. The tests were conducted on the loose aggregate, not on concrete specimens in which aggregate was incorporated. Withey suggested that these tests should be thoroughly investigated since they should not differ materially in their effects from those produced by natural agencies. He noted, for instance, that the sodium sulphate test should not be used to approximate the effects of natural freezing and thawing.

In 1928, Scholer (6) stated that, "The use of unsound aggregate produces unsound concrete, the resistance of the mortar to disintegration being only slightly effective in protecting the aggregate." In order to determine which aggregates resulted in non-durable concrete, he developed a method which tested the resistance to freezing and thawing of concrete cylinders made from the aggregates in question.

Using freezing and thawing tests of concrete, Scholer (7) continued his research on various aggregates which were suspected of containing

substances which were harmful when used in concrete. In the Kansas aggregates which he tested, he found that the most common and most destructive deleterious substances were absorptive chert in gravel and flinty concretions in limestone.

Walker and Proudley (8) studied the effects of shale on concrete durability and reviewed other investigations of shale, ocher, sandstone, and light-weight particles. They concluded that soft, friable, and non-durable particles are detrimental when used in concrete, and they noted that although investigations of these substances in concrete aggregates had yielded valuable information, these investigations had not provided a conclusive basis for fixing specification limits. Most specification limits at that time were based strictly on engineering judgment formed from a consideration of the service records of the aggregates and from a consideration of the economics of the problem in a given locality.

Runner (9), in 1937, was one of the first to seriously apply petrography to the study of deleterious substances in aggregates. He found that it was possible to determine the probable durability of aggregates by means of studies using the petrographic microscope. He made thin sections of aggregate particles and studied them under the microscope. He was able to identify the harmful types on the basis of porosity, texture, and mineral composition.

In 1938, Litehiser (10) published the results of investigations of the effects of Ohio aggregates on concrete durability. Using the freezing and thawing test developed by Scholer (6) and the sodium sulfate soundness test, he found that shale, limonite, ocher, hematite,

iron pyrites, and some varieties of chert had detrimental effects on the concrete in which they were used. He noted that not all varieties of chert were deleterious, but did not suggest a means for telling the difference between deleterious and non-deleterious cherts.

In 1939, Cantrill and Campbell (11) published the results of a concrete pavement condition survey they had conducted in Kentucky. Analysis of their data showed that serious failures of concrete pavements throughout the western part of Kentucky were due to the use of chert gravels obtained from the Tennessee and Cumberland Rivers in the western part of the state. Pavements in which these chert gravels were used often began to disintegrate within one year after construction.

The results of this survey led Cantrill and Campbell to a laboratory study of the western Kentucky cherts. They found these cherts to be extremely porous, highly absorptive, and possessed of a low specific gravity. The chert gravels passed all the standard laboratory tests for abrasion and soundness which were used at that time. These were: (a) The Los Angeles Abrasion Test, (b) the Deval Abrasion test, and (c) the Sodium Sulphate Soundness Test. Also, strength tests on chert-gravel concrete field specimens showed values comparable to those for specimens made from Ohio River gravel or crushed limestone with good service records. However, when the chert aggregate was incorporated in concrete beams and subjected to 40 cycles of freezing and thawing in water, a definite reduction in flexural strength was noted. It was thus concluded that freezing and thawing was the cause of the disintegration of these lightweight Kentucky cherts when used

in concrete pavements.

In 1940, Wuerpel and Rexford (12) published the results of their investigation of the possibility of separating durable and non-durable varieties of chert in concrete coarse aggregate by some means more precise than visual examination and more practical than microscopic analysis. In their paper, they included a symposium of related comments by other investigators. Included in this symposium are the following significant comments from the Corps of Engineers' Rock Island investigation (13):

1. "Heating and cooling of chert had absolutely no effect. This test was initiated to allay some suppositions that chert caused "popouts" in summertime due to heat of the sun followed by a cooling rain or vice versa."

2. "These results (freezing and thawing of paraffin-coated chert in mortar specimens) indicate that popouts occur only from freezing of water absorbed by the chert. This hypothesis is further verified by a comparison of the absorption and specific gravity of each type of chert with its reaction to freezing and thawing. It seems a general rule that a chert stone with an absorption greater than 3 percent or an apparent specific gravity less than 2.50 can be classified as harmful material."

Wuerpel and Rexford collected samples of cherty gravel from ten areas in the southern, central, and eastern portions of the United States. These were separated into four bulk-specific-gravity groups by heavy-liquid flotation using bromoform (specific gravity 2.86) and mono-bromo-benzene (specific gravity 1.46). The groups used had specific gravities of 2.50 plus, 2.40 to 2.50, 2.30 to 2.40, and 2.30 minus. Material in each group was analyzed microscopically and tested physically for absorptive capacity, resistance to frost action, and resistance to a magnesium sulphate soundness test. The results of these tests showed a definite increase in absorption and decrease in

soundness with lower bulk specific gravity of the samples. These trends were present for all groups lower in bulk specific gravity than 2.50, but were especially noticeable in the pebbles having a bulk specific gravity of less than 2.40.

These results compared favorably with the results of a performance survey of the exposed concrete structures in the areas from which the gravels had been obtained. A group of 100 roughly conical "popouts," each having a piece of disrupted chert at the apex, was collected from representative structures. In every case, the piece of chert had an absorption greater than 4 percent and a bulk specific gravity less than 2.40.

On the basis of this investigation, Wuerpel and Rexford concluded that the flotation method of specific gravity separation is the most practical method of separating durable from non-durable cherts. They recommended that the flotation test be used as a field test for the separation of a majority of the non-durable chert in concrete aggregate. In addition, they developed a flotation field kit to be used for this purpose.

In their discussion of the preceding study by Wuerpel and Rexford, Reagel and Willis (14) considerably contributed to the knowledge of the durability characteristics of chert. Their research was conducted on a Missouri chert-rich gravel coarse aggregate with a poor service record in concrete pavements. This aggregate, as produced for concrete pavement, had an average bulk specific gravity of 2.51 and, in the stream-wet condition, 3.8 percent absorbed moisture.

By means of a technique similar to that used by Wuerpel and Rexford (12), the saturated aggregate was separated into three fractions of different bulk specific gravities, namely, less than 2.4, 2.4 to 2.5, and over 2.5. These three coarse aggregate gravity fractions were then incorporated in 3-1/2-by 4-1/2-by-16-inch beams which, after a 28-day curing period, were subjected to consecutive cycles of freezing in air and thawing in water. After 1, 3, 5, 7, 9, and 10 cycles, the dynamic modulus of elasticity and the specimen length were determined for each of the beams.

The results of these tests showed that, for the particular aggregate employed, resistance to the freezing-and-thawing cycle used was much greater for the concrete containing the aggregate fraction of greatest bulk specific gravity than for that containing aggregate fractions of lower gravity. The results also indicated that removal of the low-gravity aggregate fractions (less than 2.50) and use of only the highest fractions (over 2.50) produced concrete that was more resistant than that in which the unseparated stream-run gravel was used.

One of the principal points brought out by Reagel's and Willis' tests was that concrete made from even the highest gravity fraction (all particles over 2.5 and an average bulk specific gravity of 2.58) of this chert-rich aggregate having a poor service record showed considerably less resistance to freezing and thawing than that of a non-chert aggregate with a good service record.

EARLY RESEARCH ON DELETERIOUS SUBSTANCES IN INDIANA AGGREGATES

In the early 1940's, the deleterious substances in Indiana's aggregates began to be exposed to comprehensive study. In 1942, Sweet and Woods (15) published the results of their thorough investigation of chert in Indiana's aggregates. They identified the chert in samples of aggregate and studied it by means of chemical and microscopic analyses, mineralogical examination, absorption tests, and freezing and thawing durability tests. They recognized the fact that all cherts are not unsound, and attempted to find a means of differentiating between durable and non-durable varieties. They considered unsound aggregates to be those which are unable to resist excessively large or permanent changes in volume when subjected to destructive agencies, particularly freezing and thawing, heating and cooling, or wetting and drying.

The first step in this study was the collection of samples from quarries and gravel deposits. Approximately four-thousand pounds of chert were secured from the six State Highway Districts in Indiana, and from sources in Illinois, Kentucky, Michigan, Missouri, Ohio, and Tennessee. The Indiana ledge rock samples were obtained from 29 quarries and highway cuts, and the gravel samples from 31 gravel deposits in all parts of Indiana.

It was decided to test the performance and properties of the quarry samples first, because the properties of the individual pieces

in each sample were reasonably uniform. Ledge cherts were obtained from quarry faces and identified geologically. A record was made of the macroscopic character of each sample, including color, luster texture, and nature of fracture. Each sample was subjected to performance and identification tests.

Performance was determined by embedding vacuum-saturated chert pebbles in mortar cubes and subjecting the cubes to alternate cycles of freezing and thawing. The blocks were frozen in water for 21 hours at -10°F., and then were immersed in water at 75° - 80°F. for three hours. This procedure was repeated until 40 cycles had been reached. At intervals the cubes were examined for signs of cracking. On the basis of these tests, the cherts were divided into two groups: (a) those which disrupted the cubes 51 to 100 percent of the time in less than 40 cycles; and (B) those which disrupted the cubes 0 to 50 percent of the time in 40 cycles. Some of the quarry chert types which proved non-durable in this test were investigated further to determine the effect of alternations of temperature.

Identification tests of the quarry cherts consisted of bulk specific gravity, absorption, degree of saturation, dye penetration, unconfined freezing and thawing, chemical analyses, and microscopic examination of thin sections. The most useful results were those from the specific gravity and absorption tests. The cherts in group A (those which disrupted the cubes 51 to 100 percent of the time in less than 40 cycles) had an average bulk specific gravity, saturated surface-dry, of 2.40 and a maximum of 2.[illegible]. Their average absorption

was 5.36 percent and the minimum absorption for group A cherts was 3.91 percent.

Samples in group B (those cherts which disrupted the cubes 0 to 50 percent of the time in 40 cycles) averaged 2.58 in bulk specific gravity, saturated surface-dry, with a minimum of 2.48. Absorption of cherts in this group averaged 1.88 percent with a maximum of 3.02 percent.

The same general performance test procedure employed on the quarry cherts was used to determine the durability of the gravel cherts. Pieces 3/4 inch to 1 inch in size were picked at random from samples of gravel chert from Indiana and other states. These were evacuated for one hour, saturated, and immersed for 24 hours. They were then embedded in two-inch mortar cubes. The mortar cubes were moist-cured for seven days and subjected to the freezing and thawing test. The gravel chert specimens that failed in this test were removed from the broken mortar and subjected to the following identification tests: color, texture, bulk specific gravity by the flotation procedure, dye penetration, apparent specific gravity, absorption, degree of saturation, and microscopic analysis. The non-failing specimens were removed from the freezing and thawing test at the end of 40 or 160 cycles, broken from the cubes, and then analyzed, using the same identification tests as were used with the failures.

A modification of the flotation method developed by Wuerpel and Rexford (12) for determining the bulk specific gravity of gravel particles was used in separating the chert samples into different

fractions on the basis of their specific gravity. Carbon tetrachloride, specific gravity 1.58, and acetylene tetrabromide, specific gravity 2.97, were mixed together to give liquids with specific gravities of 2.60, 2.55, 2.50, 2.45, 2.40, 2.35, and 2.30. A gravel specimen that had been broken out of the mortar cubes was immersed in water. After it had soaked for 24 hours, it was surface-dried and placed in the heaviest liquid (2.60). If it sank in this liquid, it was removed, and the specific gravity was recorded as 2.60 plus. If it floated on the 2.60 liquid, it was removed and placed in the 2.55 liquid. This was repeated for each piece until it sank in one of the liquids. If a piece floated in the lightest liquid (2.30), its specific gravity was recorded as 2.30 minus.

In this way it was possible to obtain a correlation between the bulk specific gravity, saturated surface-dry, of a piece of chert, and its performance in the freezing and thawing test. The results of these studies showed that the average bulk specific gravity, saturated surface-dry, of unsound chert was lower than that of durable chert. They indicated that an upper limit of 2.30 detected entirely unsatisfactory material; 2.45 detected almost all the very harmful types, and included little durable material. A limit of 2.50 included almost all the non-durable material and also a somewhat larger amount of relatively durable particles than did the 2.45 limit.

Even though Sweet and Woods found in these tests that no sharp line could be drawn between entirely sound and entirely unsound chert on the basis of specific gravity, they were able to set

up the following table as a relative measure of the probable performance of Indiana cherts in concrete based on the bulk, saturated surface-dry, specific gravity:

Below 2.30	-	Unsatisfactory
2.30 - 2.45	-	Poor
2.45 - 2.55	-	Fair
2.55 - 2.60	-	Good
Above 2.60	-	Excellent

It should be noted that in this chart proposed by Sweet and Woods, the break between "good" and "bad" cherts was found to occur at a specific gravity of 2.45. This same specific gravity is in use today by the Indiana Highway Department as the level of separation between durable and non-durable cherts.

The absorption of a piece of aggregate is ordinarily directly related to the specific gravity of the piece since, in most cases, the absorption of a material is dependent upon its porosity (16). Porosity is, in turn, directly related to the bulk specific gravity of the material. Therefore, the relative absorption of an aggregate particle may be used as an indication of the durability of the particle in the same way as bulk specific gravity.

A simple means for measuring the relative absorptivity of aggregates was used by Sweet and Woods. They selected pebbles about 1-1/2 inches in diameter, partially immersed them in a one-percent solution of water-soluble eosine dye for a given period of time, and then measured the depth of penetration of the dye. They found that the greater the penetration of the dye, the lower the durability of the chert. On the basis of these tests, they proposed the following

table of one-hour dye penetration depths to be used for predicting the relative durability of Indiana gravel cherts:

0.25" or more	-	Unsatisfactory
0.20" - 0.24"	-	Poor
0.10" - 0.19"	-	Fair
0.04" - 0.09"	-	Good
0 - 0.04"	-	Excellent

RECENT RESEARCH ON DELETERIOUS SUBSTANCES IN INDIANA AGGREGATES

In 1947, Soon (17) carried out a series of tests on coarse aggregate from eight sources of supply commonly used in concrete pavements in Indiana in which he attempted to determine the relationship of field and laboratory performance of the aggregate samples. He divided the samples into bulk specific gravity ranges by means of the heavy-liquid flotation process, and pieces from each range were embedded in two-inch mortar cubes and were subjected to freezing-and-thawing action. The cubes were placed in pans containing about an inch of water and frozen for 21 hours at zero to ten degrees Fahrenheit. They were then immersed in water at 75 to 80 degrees Fahrenheit for three hours. This procedure was repeated until failure of the cubes or until a given number of cycles was attained. In the failure of a cube, the usual process was the appearance of cracks which progressively became worse with each cycle of freezing and thawing until the fractured cube could be pulled apart by hand using a moderate amount of force.

On the basis of the results of these tests, Soon concluded that

Indiana aggregates are increasingly durable in the following order: (a) soft particles, (b) cherts, (c) limestones below 2.50 in bulk specific gravity, (d) sandstones, (e) shales, (f) limestones above 2.50 specific gravity.

Venters and Lewis (18) furthered the study of the deleterious constituents of Indiana aggregates by separating large samples of gravels into fractions having different specific gravity ranges, and testing these gravels for absorption, degree of saturation, and durability as indicated by the freezing and thawing durability test. The freezing and thawing test was conducted on 3-by-4-by-16-inch concrete beams in which different aggregate fractions were used. The test consisted of freezing in air at minus 15°F. to minus 20°F., and thawing in running tap water at 55°F. to 60°F. One cycle per day was obtained, with 16 hours freezing and 8 hours thawing. Periodic determinations of the dynamic modulus of elasticity were made to measure the deterioration of each specimen.

The results of these tests showed that the aggregates with low specific gravities were characterized by high absorptions, high degrees of saturation, and poor durability in concrete subjected to freezing and thawing. The deleterious substances in the low-specific gravity fractions consisted mainly of cherts and sandstones with lesser amount of igneous, calcareous sedimentary, and metamorphic rocks. The poor freeze-thaw durability of concrete made with the low-specific gravity aggregates was of great importance because Venters and Lewis found that those gravels in this study which had low specific gravities

also had poor field records.

As a result of their investigation, Venters and Lewis suggested that increased durability of concrete produced in actual construction could be obtained by the use of field heavy-media-separation processes. They stated that separation at 2.40 specific gravity would improve the durability of poor aggregates considerably and separation at 2.50 would result in aggregate with good durability.

Walker and McLaughlin (19) experimented further with combinations of Indiana aggregates. They used heavy-liquid separation to obtain from gravels various fractions with different minimum specific gravities. They then used these fractions, alone or in combination with good-quality crushed stone, in concrete which was tested for durability in freezing and thawing.

The gravels which were studied all had high chert contents. They contained from 10 to 70 percent chert. Although the specific gravity separation removed other low-specific gravity materials also, most of the material removed was chert.

Walker and McLaughlin found that removal of the low-specific gravity fractions from the gravel aggregates resulted in a concrete of higher durability than that made from the original, unseparated aggregate. Also, concrete made with crushed stone-gravel combinations, where the gravel used had poor service records, was made more durable with the heavy-liquid seperation. They also found that the durability of concrete made with gravel aggregates alone compared favorably with the field performance of the aggregates, thus indicating the

validity of the results of the freezing and thawing test as a relative indication of the durability of concrete.

INDIANA HIGHWAY DEPARTMENT SPECIFICATIONS GOVERNING DELETERIOUS SUBSTANCES

On the basis of the research previously described, other research and actual experience with Indiana's aggregates in service, the Indiana Highway Department's 1957 standard specifications for deleterious materials in coarse aggregates (20) have been tabulated as shown in Table I. The chert requirement in these specifications reflects the statement that not all varieties of chert are deleterious. This requirement, which is based on the specific gravity of the chert, is a direct result of the research correlating specific gravity of chert with its durability when included in concrete aggregate.

TABLE I

REQUIREMENTS FOR DELETERIOUS MATERIALS IN INDIANA S COARSE AGGREGATES*

Deleterious Material (percent by weight), not more than:	Aggregate Class A	Aggregate Class B	Aggregate Class C
Clay lumps	0.2	0.2	--
Ocher	1.0	1.0	--
Shells	0.7	1.0	--
Soft or non-durable particles[1]	4.0	4.0	--
Sum of all the above, not more than	5.0	7.0	10.0[2]
Chert (less than 2.45 bulk specific gravity)	3.0[3]	3.0[3]	--

[1] Particles which are structurally weak, such as soft sandstone, shale, limonite concretions, coal, weathered schist, or cemented gravel. The sum of all the above soft and non-durable particles shall not exceed 4.0 percent.

[2] Does not include clay lumps.

[3] Bulk specific gravity shall be determined in the saturated surface-dry condition.

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* Taken from reference 20.

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APPENDIX

A Review of the Literature on the Effect of Air Entrainment on the Durability of Concrete Made from Aggregates Containing Chert

It has been shown that entrained air occurs as minute, disconnected air bubbles uniformly distributed through the concrete. These air bubbles, when incorporated in paving concrete, produce a material which is remarkably resistant to the scaling which may be associated with the removal of snow and ice by the use of chemicals.

In the middle 1940's it was theorized that air entrainment could also be used to improve the durability of those concrete which are susceptible to freezing and thawing failure because they contain unsound coarse aggregates. Considerable research was begun at that time in an attempt to verify this hypothesis.

In 1943, Axon, Willis, and Reagel (1) fabricated air-entrained concrete test beams from four different Missouri coarse aggregates: two crushed limestones, and two chert-rich river gravels. The two limestone aggregates had good service records; one of the chert-rich gravels had a fair service record while the other had produced only concretes with poor durability. Each of these coarse aggregates was used, in a saturated condition, in three separate batches. One of these batches was made with plain portland cement and contained about 1 percent air. The other two batches contained a blend of plain cement and cement ground with 0.1 percent vinsol resin to give entrained air contents of 4 and 7 percent for the respective batches. After curing,

[illegible]

[illegible]

[illegible]

the beams from these batches were subjected to the freezing and thawing test, and their flexural strengths were measured.

Results for both limestone concretes containing entrained air showed a definite improvement in durability as measured by the freezing and thawing test. However, for concrete made with the chert-rich aggregate with a fair service record, the use of entrained air resulted in only a slight increase in durability. In the case of the chert-rich aggregate with a poor durability record, <u>the use of entrained air resulted in no appreciable improvement in durability</u>. Axon, Willis, and Reagel concluded that there is only a slight chance that air-entrainment will appreciably reduce the rate of disintegration resulting from freezing and thawing of concrete containing unsound aggregates.

In his discussion of the previously cited paper, Wuerpel (2) briefly presented the results of similar studies which he had conducted for the St. Lawrence Waterway Project. In these studies a very inferior gravel was compared with aggregate of good quality. Plain portland cements and vinsol-resin-treated cements were used with these aggregates, and it was found that the durability of the air-entrained concrete specimens containing the good aggregates was very much better than that of the plain concrete specimens containing similar aggregates, but there was a relatively insignificant improvement in the durability of the concrete with the inferior-quality gravel.

In 1944, Lindsay (3) investigated the relative durability of air-entrained portland cement concrete and regular portland cement concrete made with chert-rich aggregates. The aggregates used were stream-saturated gravels. <u>Little or no improvement in durability resulted from the use of the air-entrained portland cement</u>.

In the same year, Reagel (4) published the results of further experiments of this type. The tests conducted by Reagel were similar to those used by Axon, Willis, and Reagel (1) in 1943. As in these earlier tests, he investigated the effects of air entrainment on concrete made from two saturated chert-rich gravels and two crushed limestone aggregates as measured by resistance to laboratory freezing and thawing. His results showed that entrained air improved the durability of concrete containing either mediocre or good limestone aggregates, but caused <u>no appreciable improvement in the durability of concrete containing chert-rich aggregates</u>.

In 1947, Bugg (5) investigated the effects of air entrainment on concrete containing Indiana aggregates. He used the same techniques as previous investigators except that some batches were made using aggregates which were vacuum saturated while for other batches the aggregates were merely immersed in tap water at room temperature for 24 hours. Bugg worked with four different aggregates: two crushed limestones and two chert-rich gravels. One of the limestone aggregates had a good field performance record while the other had only a fair record. One of the chert-rich gravels contained only 9 percent chert and had a fair field performance record. The other chert-rich gravel contained 43 percent chert and had a very poor field performance record.

Concrete beams made from these aggregates and from either regular or air-entrained portland cement were subjected to the freezing and thawing test. From the results of this study Bugg concluded that under the conditions of the freezing and thawing test and with the materials used, air-entrained concrete showed slight to considerably greater

durability in every condition investigated than did regular cement concrete. However, it should be noted that the greatest improvement was shown by the immersed aggregates. Later studies by Sweet (6) have shown that 24 hour immersion does not approximate the high degree of saturation that many river gravels have at the time of their production for aggregate. Sweet also found that freezing and thawing of laboratory fabricated concrete beams produced results that were in accord with the field performance of the materials used when the aggregate was incorporated in the concrete in a moisture condition corresponding to this field saturation. At lower degrees of saturation, aggregates with poor service records were highly resistant to the laboratory freezing and thawing tests. Sweet's research indicates, therefore, that the results of the tests which Bugg conducted on the concrete made from the immersed aggregates may not be truly indicative of the situation existing in the pavement.

For the saturated aggregates Bugg's results were actually similar to those obtained in earlier studies by other investigators. He found that air entrainment improved the durability of concrete made from the limestone aggregates and from the chert-rich aggregate with a fair performance record. The improvement shown by the saturated aggregate containing 43 percent chert, however, was not appreciable except where percentages of entrained air were used which were large enough to seriously affect the strength of the concrete.

In 1948, Blackburn (7) published the results of a study of the freeze and thaw durability of seven Indiana aggregates used in concrete with varying air contents. The purpose of this study was to determine the effect of air entrainment on the durability of concrete made with

certain aggregates which were chosen on the basis of their absorptive and performance characteristics as being fairly representative of those available in Indiana. Two aggregates used by Bugg (5) were used as a means of correlating the two studies. The aggregates were incorporated in concrete test beams which were subjected to freezing and thawing as in the preceding tests. The air contents of the various concrete batches used for making these beams varied from 0.1 to 10.9 percent.

Blackburn's results closely paralleled those of Bugg. He found that air entrainment improved the resistance to freezing and thawing of concrete made from all aggregates which had only been immersed for 24 hours and thus were not fully saturated. Also, those aggregates which had been vacuum saturated but had fair to good field performance records also showed considerable improvement. Only the vacuum saturated aggregate with a poor service record failed to respond markedly to the use of entrained air. This aggregate was a river gravel containing 9 percent chert. With an air content of 0.1 percent, concrete made from this gravel was highly saturated and mortar failure resulted. Air content as high as 10.9 percent failed to make this aggregate durable in concrete when it was vacuum saturated.

The consensus of the results of the several studies reviewed in this paper seems to be that although entrained air does improve the durability of concrete made from aggregates with fair to good field performance records, it has little, if any, effect on the durability of chert-rich aggregates with poor field performance records.

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